

# Subaru constraint on circular polarization in I-band emission from the Magnetar 4U 0142+61\*

Zhongxiang WANG<sup>1</sup>, Yasuyuki T. TANAKA<sup>2</sup> and Jing ZHONG<sup>1,3</sup>

<sup>1</sup>*Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China  
wangzx@shao.ac.cn*

<sup>2</sup>*High Energy Astrophysics group, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagami-hara, Kanagawa 252-5210, JAPAN  
tanaka@astro.isas.jaxa.jp*

<sup>3</sup>*Graduate School of Chinese Academy of Sciences, No. 19A, Yuquan Road, Beijing 100049, China  
jzhong@shao.ac.cn*

(Received 2011 Nov. 22; accepted 2012 Jan. 21)

## Abstract

We present the first imaging circular polarimetry of the anomalous X-ray pulsar (AXP) 4U 0142+61 at optical wavelengths. The AXP is the only magnetar that has been well studied at optical and infrared wavelengths and is known to have a complicated broad-band spectrum over the wavelength range. The optical polarimetric observation was carried out with the 8.2-m Subaru telescope at I-band. From the observation, the degree of circular polarization  $V$  was measured to be  $V = 1.1 \pm 2.0\%$ , or  $|V| \leq 4.3\%$  (90% confidence). The relatively large uncertainty was due to the faintness of the source ( $I = 23.4\text{--}24.0$ ). Considering the currently suggested models for optical emission from magnetars, our result is not sufficiently conclusive to discriminate the models. We suggest that because linear polarization is expected to be strong in the models, linear polarimetry of this magnetar should be conducted.

**Key words:** X-rays: stars — stars: pulsars: individual (4U 0142+61) — polarization

## 1. Introduction

Supported by extensive observational studies over the past 10 years, it is generally believed that anomalous X-ray pulsars (AXPs) and soft Gamma-ray repeaters are magnetars—young neutron stars possessing ultra-high magnetic fields of  $\gtrsim 10^{14}$  G (for reviews see, e.g., Woods & Thompson 2006; Mereghetti 2008). The magnetars are remarkable, exhibiting a variety of high-energy phenomena (Kaspi 2007; Mereghetti 2008), and thus have attracted great attention after their magnetar nature was realized (Thompson & Duncan 1996). While magnetars are classified as high-energy X-ray sources, it has been learned that they also have relatively strong optical and near-infrared (NIR) emission, and are detectable at the wavelengths as long as they are either close with low extinction or in bright states (i.e., in X-ray outbursts or flares; Kaspi 2007; Mereghetti 2011).

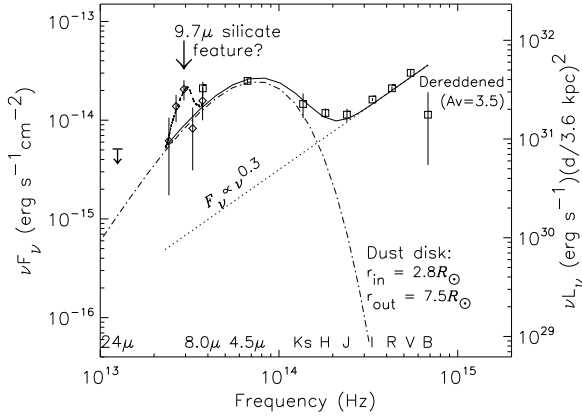
Among over 20 known magnetars (McGill AXP online catalog<sup>1</sup>), the AXP 4U 0142+61 stands out as the best studied magnetar at optical and IR wavelengths due to its relatively short distance (distance  $d \simeq 3.6$  kpc) and low extinction ( $A_V \simeq 3.5$ ; Durant & van Kerkwijk 2006a; Durant & van Kerkwijk 2006b). It was the first magnetar discovered with an optical counterpart (Hulleman et al. 2000), and its optical emission was found to be pulsed at its spin period with a pulsed fraction of 27% (Kern & Martin

2002), actually higher than that in its X-ray emission (4%–14%; Gonzalez et al. 2010). Aiming to search for supernova fallback disks around young, isolated neutron stars, Wang et al. (2006) discovered mid-infrared (MIR) emission from this magnetar with *Spitzer Space Telescope* observations, and they showed that its optical and IR spectral energy distribution (SED) can be described by a two-component model: one a power-law spectrum over optical *VRI* and NIR *J* bands probably arising from the magnetosphere of the pulsar, and one thermal blackbody-like over the 2.2–8  $\mu\text{m}$  range arising from a debris disk. Results from follow-up *Spitzer* MIR spectroscopy and 24  $\mu\text{m}$  imaging of the source were consistent with their model (see Figure 1; Wang et al. 2008). The two-component model remains controversial, as Durant & van Kerkwijk (2006c) found that the source’s NIR *K*-band flux can be highly variable with no correlated variability seen in its X-ray emission. In addition optical flux variations were also found by Durant & van Kerkwijk (2006c), although not as pronounced as that in *K*-band.

In order to fully understand optical and IR emission from magnetars, in this paper we report our observational study of another aspect of 4U 0142+61: circular polarization of I-band optical emission from the source. The AXP was observed a few times in 1994–2003, and found to have  $I = 23.4\text{--}24.0$  (Durant & van Kerkwijk 2006c).

\* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

<sup>1</sup> [www.physics.mcgill.ca/pulsar/magnetar/main.html](http://www.physics.mcgill.ca/pulsar/magnetar/main.html)



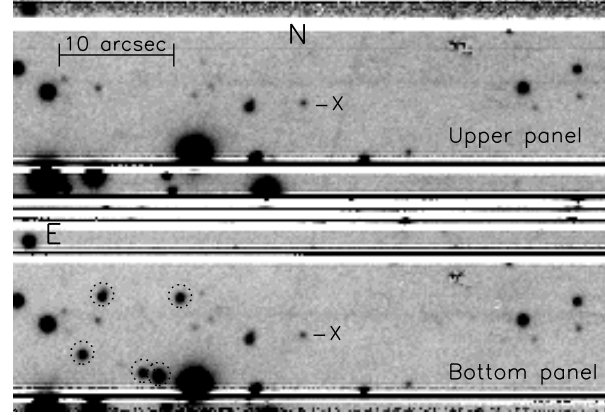
**Fig. 1.** Optical and IR broad-band and *Spitzer* IRS spectrum of the AXP 0142+61 (Wang et al. 2008). The squares are the optical, near-IR, *Spitzer* IRAC 4.5/8.0  $\mu\text{m}$  broadband fluxes (dereddened with  $A_V = 3.5$  mag), showing that the optical spectrum is consistent with being a power law (dotted line),  $F_\nu \propto \nu^{-0.3}$ , and the IR spectrum can be fit with an X-ray irradiated dust disk model (dash-dotted curve). The diamonds are the dereddened IRS flux measurements, which appear as a bump when compared to the dust disk model SED and can be fit with a silicate emission feature (dashed curve; Sloan et al. 2003). The MIPS 24  $\mu\text{m}$  upper limit is also included in the figure.

## 2. Observation and Data Reduction

Circular imaging polarimetry of 4U 0142+61 at I-band was carried out with the 8.2-m Subaru Telescope on 2009 October 24. The imaging instrument used was the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002), which can perform polarimetry with a Wollaston prism and a quarter-wave retarder inserted to the collimated beam. The Wollaston prism splits an incident beam into two orthogonally polarized beams, one ordinary (o-beam) and the other extraordinary (e-beam). The quarter-wave plate converts circular polarized light into linear polarized light by retarding one of the beams by  $1/4$  of a wave. A standard mask, provided with the FOCAS for imaging polarimetry to avoid blending of the two beams, was used. The detector was two fully-depleted-type  $2\text{k} \times 4\text{k}$  CCDs, with a pixel scale of  $0.104''/\text{pixel}$ . The detector was  $2 \times 2$  binned in our observation.

Multiple sets of five 5-min exposures of the target field were taken with the quarter-wave plate at position angle (PA)  $18^\circ$  and  $108^\circ$  alternately. Between the sets of the exposures, the telescope was dithered to avoid bad pixels on the CCDs. In total, we took 25 PA= $18^\circ$  and 20 PA= $108^\circ$  exposures. The observing conditions were good, with the seeing (FWHM of point sources) varying between  $0.4''$ – $0.8''$ .

We used the IRAF packages for data reduction. The images were bias subtracted and flat fielded. Dome flats at the two position angles were taken and used for flat fielding respectively. The images made at each PA were then positionally calibrated to a reference image that has



**Fig. 2.** Subaru circular polarization image of the AXP 4U 0142+61 at I-band. The same source field from the two polarized beams was recorded at the upper and bottom panels in the image. The counterpart to the AXP is indicated by X. Several ghost stars, marked by dotted circles, are present in the bottom panel.

the best quality, and were combined into one final image of the target field. For the sets of images at PA= $18^\circ$ , a few had the seeing larger than  $\sim 0.65''$  and were excluded from combining. In our observation, a few ghost sources appeared (see Figure 2). Such ghost sources are produced by the polarizer when a source field contains bright and saturated stars. In our case, two ghost sources were present close to the target in three images of each PA sets. To filter out the two ghost sources, pixels at each pixel position larger than the median of the images by 3 standard deviations were rejected in combining. In addition, for the PA= $108^\circ$  sets, one image with the two ghost sources was not included in combining in order to cleanly remove them. In Figure 2, a combined image of the source field is shown. The resulting FWHM of point sources in the two combined images is approximately  $0.5''$ . The total on-source times are 100 min and 95 min for the images at PA= $18^\circ$  and PA= $108^\circ$ , respectively.

We used DOPHOT (Schechter et al. 1993), a point-spread function (PSF) fitting photometry program, to measure brightnesses of our target and other in-field stars. The obtained instrumental magnitudes and uncertainties are summarized in Table 1. In addition, aperture corrections were also applied. A large radius of 7.0 pixels ( $1.46''$ ), which well included all photon counts of a point source, was used for photometry, and the aperture corrections were derived using 5 in-field, relatively bright stars (bright stars in the field were saturated). The uncertainties on the corrections were 0.021–0.035 mag, smaller than those from photometry (0.039–0.048 mag; Table 1).

We performed aperture photometry as an additional check on our results. In order to minimize uncertainties, a small aperture radius of 2.5 pixels ( $0.52''$ ) was used. Aperture corrections to a radius of 7.0 pixels were also applied. We obtained nearly the same brightness measurements, only with uncertainties generally 0.01 mag larger than those obtained from PSF fitting.

**Table 1.** PSF fitting photometry of 4U 0142+61

Sub-image	$m_{\text{pf}}$ (mag)	$\Delta m_{\text{cor.}}$ (mag)	$m_{r=7}$ (mag)
e-beam <sub>18°</sub>	24.016±0.039	0.326±0.021	23.69±0.04
o-beam <sub>18°</sub>	23.977±0.040	0.318±0.026	23.66±0.05
e-beam <sub>108°</sub>	23.923±0.049	0.352±0.026	23.57±0.06
o-beam <sub>108°</sub>	23.933±0.048	0.330±0.035	23.60±0.06

Note: instrumental magnitude  $m = 25 - 2.5 \log(\text{flux})$ ;  $m_{\text{pf}}$ ,  $\Delta m_{\text{cor.}}$ , and  $m_{r=7}$  are magnitudes obtained from PSF fitting, aperture corrections to a radius of 7 pixels, and corrected magnitudes.

### 3. Results

The Stokes  $V$  parameter measures the degree of circular polarization, which is derived from

$$V = \frac{R_V - 1}{R_V + 1},$$

where

$$R_V^2 = \frac{(I_e/I_o)_{18^\circ}}{(I_e/I_o)_{108^\circ}}.$$

Here  $I_e$  and  $I_o$  are intensities of the target in the e-beam and o-beam frames, respectively. Using the formula and intensity values obtained from PSF-fitting photometry (Table 1), we found  $V = 1.1\%$ , with an uncertainty of 2.0%. If the aperture corrected intensities are used, the result is nearly the same but with a slightly larger uncertainty,  $V = 1.4 \pm 2.4\%$ . Therefore from our observation, we found a 90%-confidence constraint of  $|V| \leq 4.3\%$  on the degree of circular polarization at I-band for 4U 0142+61.

### 4. Discussion

Using the 8.2-m Subaru telescope, we have for the first time observationally studied circular polarization in optical emission from the AXP 4U 0142+61. We found that in the source's I-band emission, Stokes  $V$  parameter was consistent with being zero, although the uncertainty was relatively large. We note that the interstellar medium can produce polarized light by scattering from aligned, elongated dust grains, but the degree of interstellar circular polarization is on the order of  $10^{-4}$  (see, e.g., Avery et al. 1975), negligible to our case. Considering that the polarimetric observation of the AXP was over 3.3 hours under the good-seeing conditions, it will be difficult to improve our measurement significantly due to the faintness of the source.

Currently, the origin of optical emission from magnetars is not clear. Eichler et al. (2002) have suggested that their optical emission could be due to synchrotron radiation from electron/positron pairs in ultra-high  $B \sim 10^{15}$  G fields, similar to radio emission from radio pulsars while scaled-up to optical wavelengths. If this is the case, since pulsars' radio emission is seen to be circularly polarized with the degree of polarization (average values over pulse profiles) in a wide range from a few percent to as high as

60% (e.g., Han et al. 1998; Gould & Lyne 1998), similar polarization would be expected in optical emission from magnetars. Indeed, Eichler et al. (2002) specifically discussed the polarization detection as a method to verify their model. Our measurement suggests zero circular polarization in I-band emission from 4U 0142+61, not supporting their model. However given the relatively large uncertainty, it is not sufficiently conclusive. We note that the degree of linear polarization of pulsars' radio emission is generally much stronger than that of circular polarization. Even at optical wavelengths, 5 pulsars were studied through linear polarimetry and found to have 5-10% degree of polarization (Słowińska et al. 2009 and references therein). Linear polarimetry of 4U 0142+61 should thus be conducted. Such an observation can be challenging. In order to conduct linear polarimetry as deep as our circular polarimetry, since imaging at four PAs is required, a significant amount of telescope time with stable, excellent seeing conditions will be needed.

In their hot corona model around magnetars, Beloborodov & Thompson (2007) have suggested two possible mechanisms for optical emission from magnetars: ion cyclotron emission or curvature emission by electron/positron pairs. In the first mechanism, ions in the corona of a magnetar absorb radio and microwave radiation at their cyclotron resonance and re-emit radiation at optical/IR wavelengths. If this mechanism is responsible for optical emission, certain degree of circular polarization might be present, depending on our viewing angle of cyclotron radiation. However it is difficult to estimate the polarization degree, thus not allowing to compare it with our derived upper limit. In the second mechanism, strong linear polarization is expected.

As a summary, we present the first optical circular polarimetry of the AXP 4U 0142+61, the only magnetar that has been well studied at optical and IR wavelengths and is known to have a complicated optical and IR broadband spectrum. From our observation, a 90%-confidence constraint of  $|V| \leq 4.3\%$  in its I-band emission is obtained. Considering the current models proposed to explain optical emission from magnetars, the upper limit is not sufficiently conclusive to discriminate the models. As strong linear polarization in optical emission is expected in the models, deep optical linear polarimetry should be conducted.

We thank the referee for valuable suggestions. This research was supported by the starting funds of Shanghai Astronomical Observatory and National Basic Research Program of China (973 Project 2009CB824800). ZW is a Research Fellow of the One-Hundred-Talents project of Chinese Academy of Sciences.

### References

- Avery, R. W., Michalsky, J. J., Stokes, R. A., Ekstrom, P. A. 1975, *AJ*, 80, 1026
- Beloborodov, A. M., Thompson, C. 2007, *ApJ*, 657, 967
- Durant, M., van Kerkwijk, M. H. 2006a, *ApJ*, 650, 1070

- Durant, M., van Kerkwijk, M. H. 2006b, *ApJ*, 650, 1082  
Durant, M., van Kerkwijk, M. H. 2006c, *ApJ*, 652, 576  
Eichler, D., Gedalin, M., Lyubarsky, L. 2002, *ApJL*, 578, L121  
Gonzalez, M. E., et al. 2010, *ApJ*, 716, 1345  
Gould, D. M., Lyne, A. G. 1998, *MNRAS*, 301, 235  
Han, J. L., Manchester, R. N., Xu, R. X., Qiao, G. J. 1998, *MNRAS*, 300, 373  
Hulleman, F., van Kerkwijk, M. H., Kulkarni, S. R. 2000, *Nature*, 408, 689  
Hulleman, F., van Kerkwijk, M. H., Kulkarni, S. R. 2004, *A&A*, 416, 1037  
Kern, B., Martin, C. 2002, *Nature*, 417, 527  
Kaspi, V. M. 2007, *Ap&SS*, 308, 1  
Kashikawa, N., et al. 2002, *PASJ*, 54, 819  
Mereghetti, S. 2008, *The Astronomy and Astrophysics Review*, 15, 225  
Mereghetti, S. 2011, *Advances in Space Research*, 47, 1317  
Schechter, P. L., Mateo, M., Saha A. 1993, *PASP*, 105, 1342  
Sloan, G. C., Kraemer, K. E., Price, S. D., Shipman R. F. 2003, *ApJS*, 147, 379  
Sławkowska, A. Kanbach, G., Kramer, M., Stefanescu, A. 2009, *MNRAS*, 397, 103  
Thompson, C. & Duncan, R. C. 1996, *ApJ*, 473, 322  
Wang, Z., Chakrabarty, D., Kaplan, D. 2006, *Nature*, 440, 772  
Wang, Z., Chakrabarty, D., Kaplan, D. 2008, 40 YEARS OF PULSARS: Millisecond Pulsars, Magnetars and More (AIP Conference Proceedings), Volume 983, 274  
Woods, P. M., Thompson, c. 2006, *Compact stellar X-ray sources* (Cambridge University Press, Cambridge) ch.14